ERDC/CRREL TR-14-24

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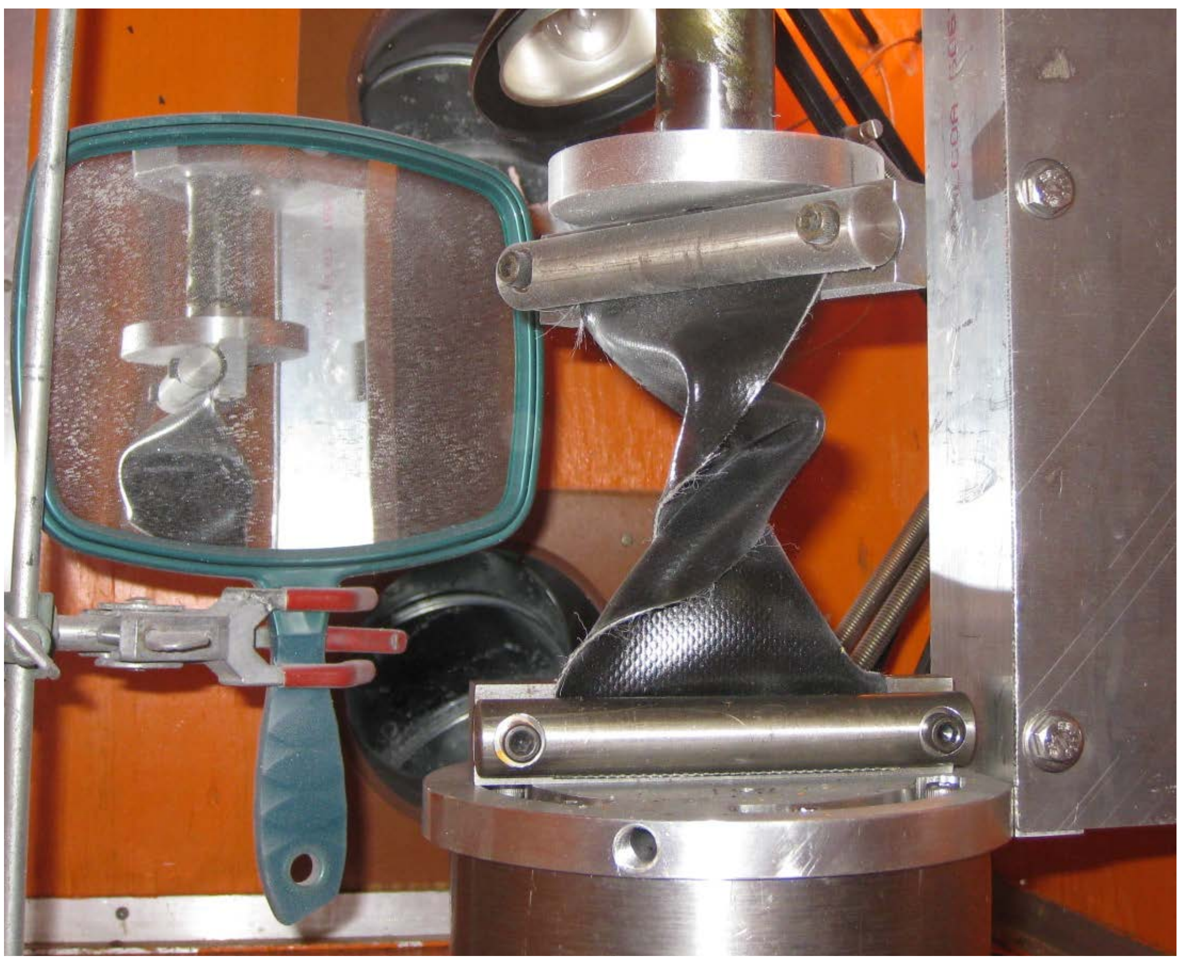
Low-Temperature Flex Durability of Fabrics for Polar Sleds

James H. Lever, Jason C. Weale, and Glenn Durell

October 2014



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Final Report

Prepared for National Science Foundation, Division of Polar Programs,
Antarctic Infrastructure and Logistics
Arlington, VA 22230

Under Engineering for Polar Operations, Logistics, and Research (EPOLAR)
EP-ANT-12-47, “Bladder Material Low-Temperature Flexibility Tests,” and
EP-ANT-13-46, “Models and Materials for SPoT Cargo and Fuel Sleds”

Abstract

Lightweight fuel-bladder sleds are remarkably efficient and less expensive than conventional steel sleds for Antarctic resupply traverses. However, a significant fraction of fuel bladders develop cracks after being emptied and folded for return transport and storage. We conducted low-temperature flex-durability tests of existing and candidate bladder materials to understand the fold-cracking problems and to seek more durable materials. The fabric specimens underwent repeated cycles of severe twisting and folding at −40°C, after which the specimens were checked for leaks by using an air-permeability test. Remarkably, the existing bladder material could withstand hundreds of cycles before cracking and leaking, and it performed better than tested alternatives. We speculate that months-long folded storage of bladders causes stress-relaxation in the polymer coating at tight folds, and pre-season unfolding then induces tensile cracking. In 2013, the South Pole Traverse (SPoT) acted on our recommendation to transport and store empty bladders inflated. They reported very promising results: no leaks in bladders and shorter preparation times for sled re-use. The flex-durability tests also identified very durable materials to build enclosure pouches for air-ride cargo sleds (ARCS). ARCS have the potential to transport rigid and out-size cargo as efficiently as fuel in bladder sleds.

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Preface

This study was conducted for the National Science Foundation (NSF), Division of Polar Programs, Antarctic Infrastructure and Logistics under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-12-47, “Bladder Material Low-Temperature Flexibility Tests,” and EP-ANT-13-46, “Models and Materials for SPoT Cargo and Fuel Sleds.” The technical monitor was George L. Blaisdell, Chief Program Manager, NSF-PLR, U.S. Antarctic Program.

The work was performed by Dr. James Lever and Jason Weale (Force Projection and Sustainment Branch, Dr. Edel Cortez, Chief) and Glenn Durell (Engineering Resources Branch, Jared Oren, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Janet Hardy was the program manager for EPOLAR. Dr. Justin Berman was Chief of the Research and Engineering Division of ERDC-CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

The authors thank J. S. Buska and C. D. Aall for their helpful reviews of the manuscript. We also thank Aero Tec Laboratories, Aircraft Rubber Manufacturing, and Federal Fabrics-Fibers for providing samples of existing and candidate materials for lightweight polar fuel and cargo sleds.

COL Jeffrey R. Eckstein was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

ARCS	Air-Ride Cargo Sleds
ARM	Aircraft Rubber Manufacturing
ASTM	American Society for Testing and Materials
ATL	Aero Tec Laboratories
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics and Research
ERDC	Engineer Research and Development Center
FFF	Federal Fabrics-Fibers
GrIT	Greenland Inland Traverse
HMW-PE	High Molecular Weight Polyethylene
MTS	Material Testing Systems
NSF	National Science Foundation
PIG	Pine Island Glacier
SPoT	South Pole Traverse

Unit Conversion Factors

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms

Executive Summary

The economic payback of Antarctic resupply traverses depends strongly on the payload efficiency (payload carried per unit towing force) and the life-cycle costs of the sleds employed. Lightweight fuel-bladder sleds have demonstrated remarkably high payload efficiency relative to conventional steel sleds. They have also demonstrated good strength and durability flexing over large sastrugi, and no ruptures have occurred over many thousands of miles of use. However, a significant fraction of fuel bladders develop cracks after being emptied and folded for return transport and storage. These cracks tend to lie predominantly along folds and require time-consuming patching before reusing the bladders. Traverse crews retire bladders if the cracks are too numerous to repair with confidence. This problem reduces bladder life to well below that expected from outbound durability considerations, thus increasing life-cycle costs.

We conducted low-temperature flex-durability tests of existing and candidate fuel-bladder materials to understand the nature of fold-cracking problems and to seek more durable materials. The tests derived from American Society for Testing and Materials (ASTM) Standard F392, *Standard Practice for Conditioning Flexible Barrier Materials for Flex Durability* (ASTM International 2011), often called “Gelbo” tests, with simple modifications to test fabrics that stiffen significantly at low temperatures. The fabric specimens underwent repeated cycles of severe twisting and folding at −40°C, after which the specimens were checked for leaks by using an air-permeability test.

We expected the severe twisting and folding at −40°C to produce cracks in specimens of the existing bladder material (single-layer polyurethane-coated fabric) within a few cycles. Remarkably, the specimens could withstand hundreds of cycles before cracking and leaking, and the existing bladder material performed better than tested alternatives. We also could not replicate cracking of existing bladder material by cold soaking at −70°C and testing at −40°C, indicating that the polymer coating does not undergo irreversible brittle transition at over-winter storage temperatures.

In addition, we attempted to simulate cyclic stressing of folded bladders during return transport. However, specimens folded lengthwise, clamped

in the apparatus, and subjected to 10,000 vibration cycles at −40°C (± 0.5 in. stroke at 0.5 s periods) did not crack.

We speculate that months-long folded storage of bladders causes stress-relaxation in the polymer coating at tight folds, and pre-season unfolding then induces tensile cracking. Tests conducted to simulate this process produced creases but no cracks in areas of tight double folds. Nevertheless, longer stress-relaxation times and the resulting tensile stresses during unfolding could be sufficient to crack the material in some fraction of the many such tight folds that occur in each stored bladder.

Some bladder-material alternatives tested included two-layer systems (impermeable inner liner enclosed in durable fabric shells). Previous tests (Weale et al. 2011) identified a very durable two-layer system to construct air-filled pontoons for air-ride cargo sleds (ARCS). However, the Gelbo tests showed that these two-layer systems are not viable substitutes for existing fuel bladders.

The Gelbo tests also identified very durable polymer-coated fabrics to construct pouches for ARCS that enclose the pontoons. ARCS have the potential to transport rigid and out-size cargo as efficiently per unit weight as fuel in bladder sleds.

We provided the following recommendations based on low-temperature flex-durability (Gelbo) tests of existing and candidate sled fabrics:

- Antarctic traverses should continue to use fuel bladders constructed from ATL-853C (black) polyurethane-coated fabric as supplied by Aero Tec Laboratories.
- If possible, transport and store empty bladders unfolded or inflated to reduce the potential for material failure (cracking and leaking) resulting from unfolding the bladders. Compare rates of bladder failures with traditional folded storage.
- Continue to procure ARCS pontoons constructed using the two-layer air beam system developed by Federal Fabrics-Fibers (FFF).
- Procure ARCS pouches constructed using material #18 from FFF or its equivalent as assessed through low-temperature Gelbo tests.

In 2013, the South Pole Traverse (SPoT) acted on our recommendation to transport and store empty bladders inflated. They filled emptied bladders with air at South Pole for return transport and stored entire sled assemblies over winter at McMurdo with the bladders inflated and sleds secured against wind loads.

Feedback from the SPoT crew was very encouraging: inflated bladders retained air pressure over winter, and assembled sleds were easy to extract from the surrounding snowdrifts. Essentially, the bladder sleds were ready to use right out of storage by simply filling bladders with diesel fuel—no assembly required. Compared with folded storage, this method could significantly increase bladder life plus reduce the labor cost to disassemble, fold, store, unfold, inspect, and reassemble bladders on sleds each year.

1 Introduction

Flexible fuel bladders strapped to flexible sheets of high molecular weight polyethylene (HMW-PE) have proven to be the most efficient and cost-effective way to transport fuel from McMurdo Station to South Pole Station, Antarctica (Figure 1). Compared with conventional steel sleds, fuel-bladder sleds are one-sixth the cost, one-tenth the weight, and triple the fuel delivered per towing tractor (Lever and Weale 2012). The two South Pole Traverse (SPoT) fleets each require about sixty 3000 gal. fuel bladders costing just under $10,000 each. To date, these bladders consist of single-layer, polyurethane-coated fabric and have all been manufactured and supplied by Aero Tec Laboratories (ATL).

Figure 1. Fuel-bladder sleds ready for outbound transport on the South Pole Traverse from McMurdo Station to South Pole Station. The sleds consist of dual 3000 gal. fuel bladders strapped to 8 ft wide × 68 ft long × 0.5 in.-thick HMW-PE sheets towed through steel towplates. Sleds with black bladders produce lower sliding friction owing to solar gain, so SPoT is systematically replacing older tan bladders with black ones constructed from similar polyurethane-coated fabric.

With engineering support from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), SPoT pioneered the use of bladder sleds to transport fuel over natural polar snowfields. Initial discussions with ATL made it clear that while the bladders are very strong, low-temperature flexing was well outside their intended use and prior experience. Consequently, prior to fielding the current generation of bladder sleds, CRREL researchers conducted rigorous laboratory tests in 2008 and again in 2010 to confirm that the bladders would not rupture when towed over large sastrugi and would provide a reasonable service life (Lever et al. 2010). Field experience has validated these findings: no ruptures have occurred during five seasons of operational use, totaling about 400,000 bladder miles across demanding Antarctic terrain, and very few bladders have developed leaks warranting in-field fuel transfer.

However, 10%–20% of bladders annually require patching to repair cracks from the previous season's use, and owing to severe cracking, several bladders were retired after less than two years of service. Standard SPoT procedures are to roll or gently fold bladders after fuel off-load at South Pole station and then strap several bladders together for return transport. The returned bladders are stored overwinter at McMurdo station in unheated containers at ambient temperatures to about −60°C (Figure 2). The crew inspects each bladder at the start of the next season, which is when they discover the cracks. Because so few bladders leak during outbound or return fuel transport, apparently return transport and over-winter storage of rolled/folded bladders causes the cracking. Possible cracking mechanisms include rolling or folding at South Pole temperatures (about −30°C), cyclic stressing during return transport over rough snow, and unfolding of stored bladders at the start of the next season.

Figure 2. Fuel bladders removed from over-winter storage at McMurdo prior to inspection. Note the tight folds at corners despite efforts at South Pole to roll the emptied bladders rather than to fold them.

Discussions with ATL revealed that low-temperature flex-durability is not part of their standard specifications when procuring bladder materials, and performance at temperatures less than 0°C could vary with the source of the material. All polymer-coated fabrics tend to become brittle as temperatures drop below freezing, with performance dependent on coating formulation and additives used to improve bonding to substrate fabrics. ATL was therefore interested in our assessment of low-temperature flex-durability and suggested that an alternative, elastomer-coated fabric produced by their affiliate Aircraft Rubber Manufacturing (ARM) might perform better.

We conducted low-temperature flex-durability tests of existing and candidate fuel-bladder materials to understand the nature of fold-cracking problems and to determine whether more durable materials exist. We adapted American Society for Testing and Materials (ASTM) Standard F392, *Standard Practice for Conditioning Flexible Barrier Materials for Flex Durability* (ASTM International 2011), making simple modifications to test fabrics that stiffen significantly at low temperatures. Tests conducted under ASTM F392 are often called "Gelbo" tests after a trade name for the test fixture. The fabric samples underwent repeated cycles of severe twisting and folding at −40°C, after which we checked the samples for leaks by using an air-permeability test. We initially established a durability baseline (i.e., cycles needed to cause leaks) for the existing ATL bladder materials. We then tested other candidate bladder materials to determine relative durability.

We also obtained and tested polymer-coated fabrics considered for use in prototype air-ride cargo sleds, or ARCS (Figure 3). The ARCS suspension consists of air-filled pontoons housed in fabric pouches that secure the cargo deck to the underlying plastic sled (Figure 4). The Greenland Inland Traverse (GrIT) and the Pine Island Glacier (PIG) traverse both used ARCS to transport rigid cargo in 2011–12. The vendor, Federal Fabrics-Fibers (FFF), supplied its standard two-component "air-beam" technology for the cylindrical pontoons (impermeable inner liners enclosed in durable fabric shells). These pontoons performed extremely well over both traverses with no significant leaks reported. However, the fabric pouches were new products, built to our specifications, and FFF based its fabric selection on experience and suppliers' spec sheets. The resulting pouches were stiff to handle at low temperatures, making outdoor assembly difficult, and cracks and tears developed during use as the pouches flexed over rough snow (Figure 5). We thus sought more durable pouch fabrics, and FFF provided several candidate materials to evaluate using Gelbo tests.

Figure 3. Prototype ARCS deployed on GrIT12 (upper) and PIG11–12 (lower) to transport rigid cargo over snow. Both ARCS used air-filled pontoons enclosed in fabric pouches as lightweight compliant suspensions between the cargo decks and the underlying HMW-PE sheets. The pontoons consist of cylindrical woven-fabric shells enclosing impermeable inner liners.

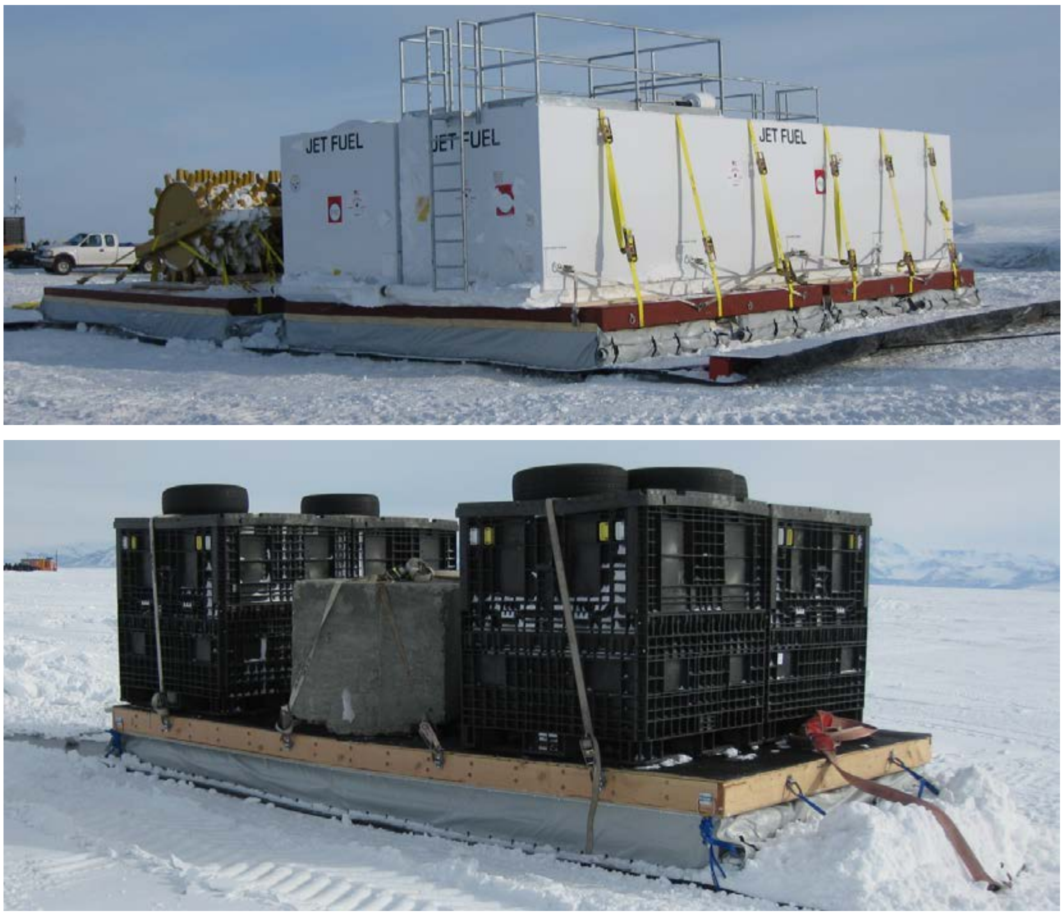


Figure 4. Construction of tube-in-pouch suspension for ARCS. Left: cylindrical air-filled pontoons (black) slide inside fabric pouches (gray), which bolt between HMW-PE sheets and wooden cargo decks. Right: each pontoon consists of a woven outer shell (black) and an impermeable inner liner (clear) as shown with this short sample.

Figure 5. The polymer-coated fabric used for prototype ARCS pouches was stiff to handle at low temperatures and tended to crack when flexed over rough snow. Two GrIT12 pouches tore along joints with underlying sleds (tear circled in red here), a result of brittle fabric behavior at low temperature and stress concentrations at the corners.

2 Test Methods

All tests were performed in a temperature-controlled chamber on a closed-loop, electro-hydraulic Material Testing Systems (MTS) machine. It has a 25,000 lb actuator with a 6 in. stroke. The insulated test chamber measures 20 in. wide, 36 in. deep, and 40 in. high. A cascade refrigeration system circulated cold air and used a thermocouple in the exiting air stream as feedback to control chamber temperature (±0.1°C). The chamber is capable of reaching and maintaining −70°C.

ASTM F392 (ASTM International 2011) specifies tests to condition flexible barrier materials to determine flex resistance. Standard specimens measure 8 × 11 in. and are wrapped and clamped around 3.5 in. diameter mandrels spaced 7 in. apart in an apparatus designed to combine rotation and compression of the specimen. The standard prescribes 440° of rotation during the first 3.5 in. of compression followed by straight compression for 2.5 in. “Gelbo Tester” is the trade name for an apparatus that can produce the prescribed motion and has become synonymous with the test itself.

These tests are not routinely conducted at temperatures relevant to cold-region needs, and most manufacturers do not know how various combinations of woven fabric and bonded coatings will perform when flexed at temperatures below 0°C. We chose a baseline temperature of −40°C to simulate the low end of Antarctic and Arctic summer service. We found during initial trials that the relatively thick (about 0.060 in.) bladder materials were very stiff when wrapped into a 3.5 in. diameter cylinder and could slip the mandrel clamps or shear the cam-follower used to rotate the specimen. We thus switched to 3.5 in. wide × 8 in. long rectangular specimens and modified the mandrels to clamp these securely. We also reduced the final straight compression to 2.0 in. to prevent the fabric from jamming against the mandrel clamps. Because polymers tend to transition to brittle behavior at high deformation rates, we chose a relatively fast cycle time of 4 s (i.e., 2 s to rotate and compress the specimen and 2 s to reverse the motion). The resulting rapid twisting and compression of the specimens appeared to be very severe and imposed more demanding flexing of the material than standard field use (Figure 6).

Figure 6. Photo sequence of black bladder material undergoing Gelbo flex tests at −40°C. The apparatus imposed 440° rotation during the first 3.5 in. of compression followed by straight compression for 2.0 in. Each cycle took 2 s to compress the specimen and 2 s to reverse the motion (4 s total cycle time). A mirror allowed visual inspection of the back of the specimen without removing it from the apparatus.

Sample preparation consisted simply of cutting several specimens of the material to size and cold-soaking them at −40°C in the chamber for several hours. In turn, we clamped each specimen in the mandrels, subjected it to a set number of cycles (1–1000), and then removed it from the chamber for assessment.

ASTM F392 (ASTM International 2011) does not specify how to assess the effects of flexing on the specimens. We chose to use visual inspection followed by an air-permeability test to assess relative flex durability. After conditioning, we visually inspected each specimen for signs of cracking or delamination of the coating from the embedded woven fabric. We marked such regions on the specimen then conducted a check for air leakage at room temperature.

The leakage-test apparatus consisted of two aluminum disks with embedded O-rings with the upper disk connected to an air reservoir (Figure 7). After pressurizing with air, we sealed off the air reservoir and monitored disk pressure over several minutes to assess the leakage rate. The difference in leakage rates between intact and cracked specimens was readily apparent (Figure 8).

Figure 7. After conditioning material specimens in the Gelbo flex apparatus for a number of cycles, we removed and inspected them for cracks (left) then clamped over the cracked areas with a leakage-test apparatus to assess failure (right).

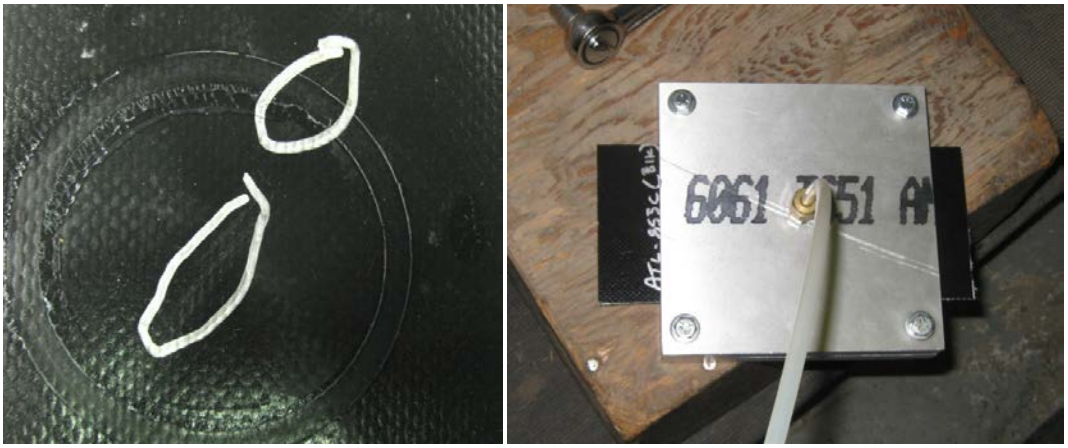
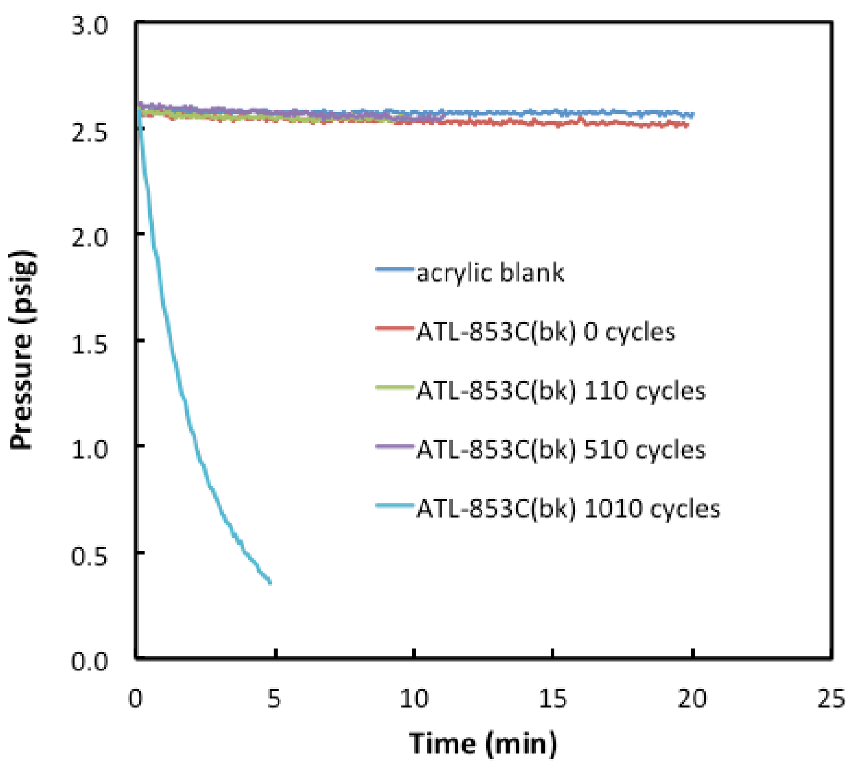


Figure 8. Leak-test results after flexing ATL-853C (black) specimens for 110–1010 cycles at −40°C. Cracked specimens showed very rapid leakage (pressure drop) during the first few minutes after sealing off the air reservoir compared with leakage rates of intact specimens (untested or tested but not cracked). The uppermost curve shows the low leakage rate of the apparatus itself using a smooth acrylic blank; intact specimens produce similarly low leakage rates.



3 Materials Tested

The product information provided by the material suppliers varied from general to very specific. For all materials, we can state the general category (e.g., polymer- or elastomer-coated fabric), color, thickness, and recommended application. Table 1 summarizes this information. FFF provided additional material properties (polymer type, fabric type and weave, tensile strength, etc.), which improved our ability to assess their potential for use as ARCS components. We hold this information as confidential and do not report it here.

ATL constructed the existing SPoT and GrIT fuel bladders from a polyurethane-coated fabric, which they designate as ATL-853C. They provided sample sheets in both tan (0.063 in. thick) and black (0.067 in. thick).

On ATL's recommendation, we requested and obtained samples of an elastomer-coated fabric produced by a company affiliate, ARM. The material was black, ranged from 0.053 to 0.064 in. in thickness, and was designated ARM-FAB200.

FFF provided a suite of materials for testing, some of which they recommended for possible use as fuel bladders and some for ARCS (pontoons or pouches).

Table 1. Materials tested.

Source	Sample #	Sample Name	Type	Color	Thickness (in.)	Suggested Application	Use
ATL		ATL-853C (tan)	polyurethane-coated fabric	tan	0.063	fuel bladders	SPoT and GrIT bladders
ATL		ATL-853C (black)	polyurethane-coated fabric	black	0.067	fuel bladders	SPoT and GrIT bladders
ARM		ARM-FAB200	elastomer-coated fabric	black	0.053–0.064	fuel bladders	
FFF	1	102411C	polyurethane-coated fabric	tan	0.030	fuel bladders and ARCS pouches	
FFF	2	Xtrm Ply TPU 21 Oz	polyurethane-coated fabric	black	0.025	fuel bladders	
FFF	3	43808A TPU	polyurethane-coated fabric		0.015	fuel bladders and ARCS pouches	
FFF	4	R-Value Prototype 5B	PVC-coated fabric		0.033	ARCS pouches	
FFF	5	R-Value Prototype 5C	PVC-coated fabric		0.029	ARCS pouches	
FFF	6	H16-679	PVC-coated fabric	Two-tone gray, green	0.019	ARCS pouches	GrIT12 and PIG11–12 pouches
FFF	7	IS-FAB	coated polyethylene woven cloth	white	0.012	ARCS pouches	
FFF	8	58219	polyether film	clear	0.010	bladder and pontoon liners	
FFF	9	58219	polyether film	clear	0.020	bladder and pontoon liners	
FFF	10	58219	polyether film	clear	0.030	bladder and pontoon liners	
FFF	11	58226	polyether film	clear	0.010	bladder and pontoon liners	
FFF	12	58226	polyether film	clear	0.020	bladder and pontoon liners	
FFF	13	58226	polyether film	clear	0.030	bladder and pontoon liners	
FFF	14	58315	polyether film	clear	0.010	bladder and pontoon liners	PIG11–12 pontoon liners
FFF	15	58315	polyether film	clear	0.015	bladder and pontoon liners	GrIT12 pontoon liners
FFF	16	FAB-2400	coated polyester woven cloth	black		bladder and pontoon outer shells	GrIT12 and PIG11–12 pontoon shells
FFF	17	10508-2460RND	polyurethane-coated fabric	tan	0.030	ARCS pouches	
FFF	18	10512-2460BLK	polyurethane-coated fabric	black	0.029	ARCS pouches	GrIT13 pouches

4 Test Results

4.1 Fuel-bladder materials

We tested the existing bladder materials (ATL-853C) to establish a baseline for low-temperature flex durability. We normally cut three specimens of each material and subjected successive specimens to cumulatively more cycles. Table 2 summarizes the results.

Table 2. Gelbo test results for existing bladder materials.

Sample	Temp (°C)	Total # Cycles	Leak
ATL-853C tan	−40	10 510 1010	No No No
ATL-853C black	−40	10 510 1010	No No Yes
ATL-853C tan	−50	10 50 100	No No No
ATL-853C black	−50	10 50 100	No No No

The Gelbo test imposes severe flexing and folding of the specimens, so we had expected to see failure (cracking and leaking) within a few cycles at −40°C. We were thus surprised to find that the existing bladder materials survived 510–1010 cycles without failure. We therefore repeated the tests with new specimens at −50°C and found that both materials survived 100 cycles without failure. This temperature is well below that normally encountered at South Pole when the bladders are emptied and folded, suggesting that simply folding the bladders does not cause the observed cracks.

By contrast, we were disappointed in the performance of the ARM elastomer-coated fabric, having expected it to perform better than the ATL materials. The material cracked and leaked after only one cycle at −40°C (three repeated tests) and shattered after a single cycle at −50°C. Table 3 summarizes these results. Figure 9 compares post-test ATL and ARM specimens tested at −50°C.

Table 3. Gelbo test results for ARM elastomer-coated fabric.

Sample	Temp (°C)	Total # Cycles	Leak
ARM-FAB200	−40	1 1 1	Yes Yes Yes
ARM-FAB200	−50	1	Yes (shattered)

Figure 9. ARM-FAB200 specimens shattered and delaminated after one Gelbo cycle at −50°C (right), while specimens of existing bladder materials (ATL-853C) survived 100 cycles at −50°C without cracking and leaking (left and center).

FFF suggested that Samples 1–3 (Table 1), all single-wall polyurethane-coated fabrics, be evaluated as possible fuel-bladder materials. Test results at −40°C (Table 4) indicate that these do not perform as well as existing bladder materials.

Table 4. Gelbo test results for FFF single-wall materials considered for use as fuel bladders.

Sample No.	Sample Name	Temp (°C)	Total # Cycles	Leak
1	102411C	−40	10 510	No Yes
2	Xtrm Ply TPU 21 Oz	−40	10 130	No Yes
3	43808A TPU	−40	10 220	No Yes

FFF also provided materials they considered suitable for two-wall fuel bladders: Samples 8–15 as impermeable liners and Sample 16 as an external protective shell (Table 1). Indeed, some of these materials (Samples 14–16) were components of the well-performing pontoons deployed on PIG11–12 and GrIT12. We first tested the liners individually and then combined the best-performing one with a layer of shell material to assess whether the shell increased abrasion. Table 5 summarizes the results, which indicate that these materials also do not perform as well as existing bladder materials when used as a liner-shell system.

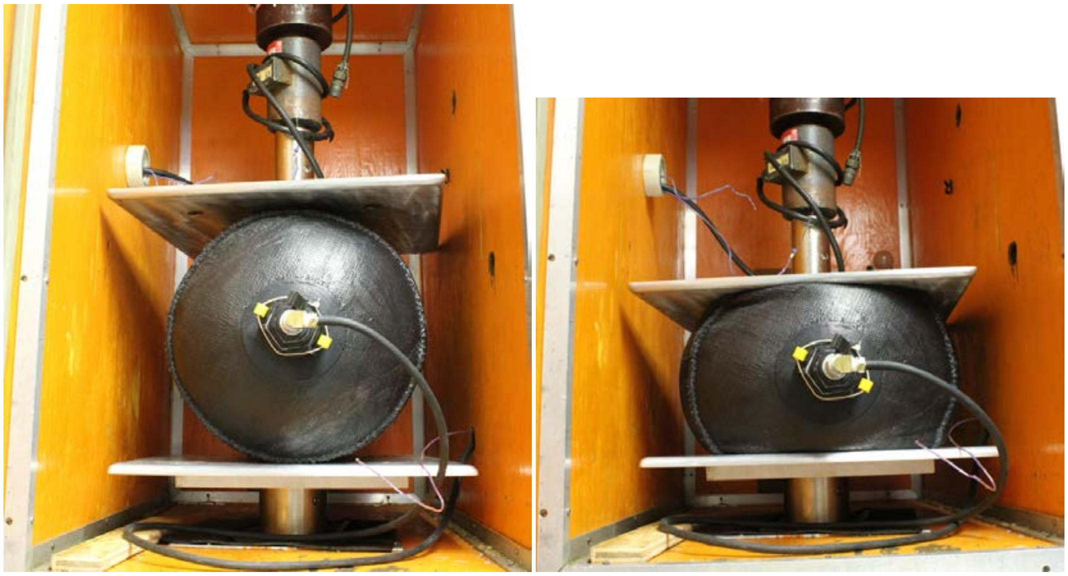
Table 5. Gelbo test results for FFF pontoon liner and shell materials considered for use as fuel bladders.

Sample No.	Sample Name	Temp (°C)	Total # Cycles	Leak
14	58315, 0.010 in. (PIG11–12 pontoon liners)	−40	100	Yes
15	58315, 0.015 in. (GrIT12 pontoon liners)	−40	100 500 1000	No No Yes
15 and 16	58315, 0.015 in., and FAB2400 (GrIT12 pontoon liners and shells)	−40	10 500	No Yes

4.2 ARCS materials

ARCS pontoons flex but do not twist and fold during field use. Consequently, the Gelbo test is an extreme durability test for pontoon materials. Indeed, prior to deploying the PIG11–12 and GrIT12 ARCS, FFF provided us with a 12 in. diameter sample pontoon constructed using materials designated as Sample 14 (liner) and Sample 16 (shell) in Table 1. This sample pontoon derived from FFF's technology to produce air beams for rapidly deployable shelters. We subjected it to cyclic compression (5 in. stroke, 2–8 s cycle time) at −40°C in the same cold chamber later used for the Gelbo tests (Weale et al. 2011). The test did cause the sample pontoon to fold on itself at some locations (Figure 10). Nevertheless, it survived 10,000 cycles without leaking. This result suggested excellent durability, and subsequent field experience using 18–24 in. diameter tubes from FFF as ARCS pontoons has confirmed this conclusion.

Figure 10. Low-temperature compression tests on a sample ARCS pontoon built by FFF using materials designated Samples 14 and 16 here (Weale et al. 2011). The photo on the right in Figure 4 shows the liner-shell construction of this pontoon sample.



FFF initially provided Samples 4–7 for consideration as pouch material for ARCS and provided Samples 17–18 once testing began. By this point, PIG11–12 and GrIT12 had pouches constructed from Sample 6, so it provided a performance baseline. This material was stiff to handle at low temperatures, making outdoor assembly difficult, and cracks and tears developed during use as the pouches flexed over rough snow (Figure 5). We were therefore seeking materials with better flexibility and durability at low temperatures. Note that the pouch materials can be porous, so we inspected the specimens for signs of damage (e.g., obvious cracking or delaminating of the polymer coatings) rather than testing them for leaks. Table 6 summarizes the Gelbo test results of candidate pouch materials.

Samples 4–5 performed no better than the baseline Sample 6 material. Sample 7 is a woven fabric with no polymer coating, and it showed no signs of damage after 1510 cycles. However, it must be sewn at its seams to form ARCS pouches rather than heat welded as for the other samples (all polymer-coated fabrics). Higher fabrication costs thus offset its evident durability.

Samples 17–18 both showed improved durability and hand-flexibility at −40°C compared with the baseline material (Sample 6). The main difference between these materials is the color of the coating, tan and black, respectively. Because black pouches will absorb sunlight better than tan ones and thereby stay more flexible in the field, we recommended Sample 18 for use in the next series of ARCS pouches.

Table 6. Gelbo test results for FFF materials considered for use as ARCS pouches.

Sample No.	Sample	Temp (°C)	Total # Cycles	Damage
4	RvaluePrototype5B	−40	10	Yes
5	RvaluePrototype5C	−40	10	Yes
6	H166 green/gray (PIG11–12 and GrIT12 pouches)	−40	10	Yes
7	IS-FAB MAIWEVE (must be sewn)	−40	10 510 1510	No No No
17	10508-2460RND	−40	10 510	No minimal
18	10512-2460BLK (GrIT13 pouches)	−40	10 110 510	No No minimal

5 Attempts to Replicate Fuel-Bladder Failures

As noted, the existing ATL bladder materials survived hundreds of Gelbo cycles at −40°C and 100 cycles at −50°C without failures (cracks and leaks). What then causes bladder failures after they are emptied at South Pole?

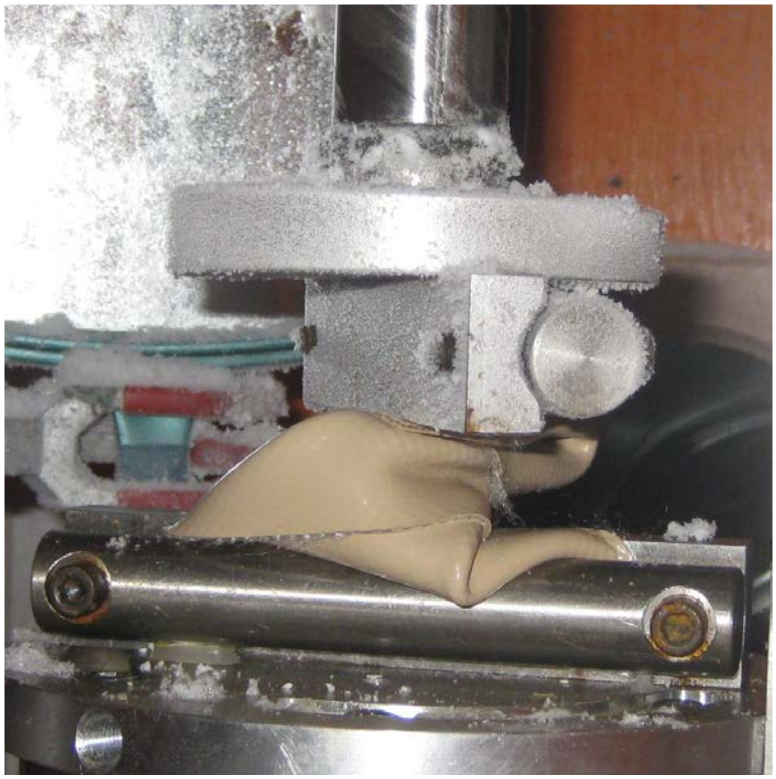
We considered several possibilities:

- Vibration during return transport
- Irreversible brittle transition of polymer coating during over-winter storage
- Stress relaxation when folded, then tensile cracking when opened

Described here are several ad-hoc tests that we conducted on ATL-853C tan and black specimens to attempt to mimic these conditions. Although we were generally unable to identify the mechanism causing field failures of the bladders, the tests did provide some insight.

To simulate vibration during return transport, we cold-soaked a specimen at −40°C, installed it in the Gelbo apparatus, and slowly brought down the crosshead until it had completed its full 440° rotation and 5.5 in. of total stroke (i.e., half a Gelbo cycle). We left it compressed in this position overnight. The MTS machine then cyclically executed ±0.5 in. cycles at 0.5 s periods (4.5–5.5 in. stroke range at 2 Hz) for 10,000 cycles. Despite the high cycle counts, these faster, shorter cycles did not produce leaks in the specimens. That is, they were less damaging to the material than full Gelbo cycles at 4 s periods. We even repeated these tests with specimens folded lengthwise once, so they more closely represented a folded fuel bladder (Figure 11). Again, no failures resulted after 10,000 cycles. We conclude that vibration of folded bladders during return transport is unlikely to cause the observed failures.

Figure 11. A specimen of existing bladder material (ATL-853C tan) undergoing vibration tests at −40°C. The specimen was folded lengthwise before it was clamped in the apparatus. Notice the sharp corner in the folded and compressed specimen. These specimens (tan and black) survived 10,000 vibration cycles without failures (cracks and leaks).



To simulate irreversible brittle polymer change during over-winter storage, we placed specimens in the apparatus, slowly executed a half-Gelbo cycle (440° rotation and 5.5 in. total stroke) then cold-soaked the specimens at −70°C for 30 min. We then raised the chamber temperature to −40°C and conducted full Gelbo tests as usual (440° rotation, 5.5 in. total stroke, 4 s period). The specimens essentially behaved as before (Table 2), with tan specimens surviving 1510 cycles without leaking and black specimens leaking after 1000–1500 cycles. That is, simply being cold-soaked at −70°C did not alter low-temperature durability of the bladder materials.

Does time-scale matter? Bladders left folded over-winter in McMurdo would have 6–7 months to accommodate stresses at folded corners (Figure 2). Material initially under compression in the sharp-radius interior corners probably relaxes to a neutral state during this time. When unfolded at the start of the next season, the corner would then experience high tensile stresses as it opens.

We attempted to simulate these conditions by double-folding specimens at room temperature, clamping them and allowing them to relax at room temperature for 1–2 days (Figure 12). We then cold-soaked the folded specimens at −40°C for several hours and abruptly opened them at −40°C. The material on the inside of the double folds was creased, but no cracks formed, and the specimens did not leak (Figure 13). Interestingly, the specimens tended to fold-up after being opened, suggesting that some stress-relaxation did occur while they were clamped at room temperature (Figure 14).

Figure 12. Specimens of bladder material double folded, clamped, and allowed to relax at room temperature.

Figure 13. Bladder material creased but did not crack and leak at the inside corners of double folds when opened at −40°C.

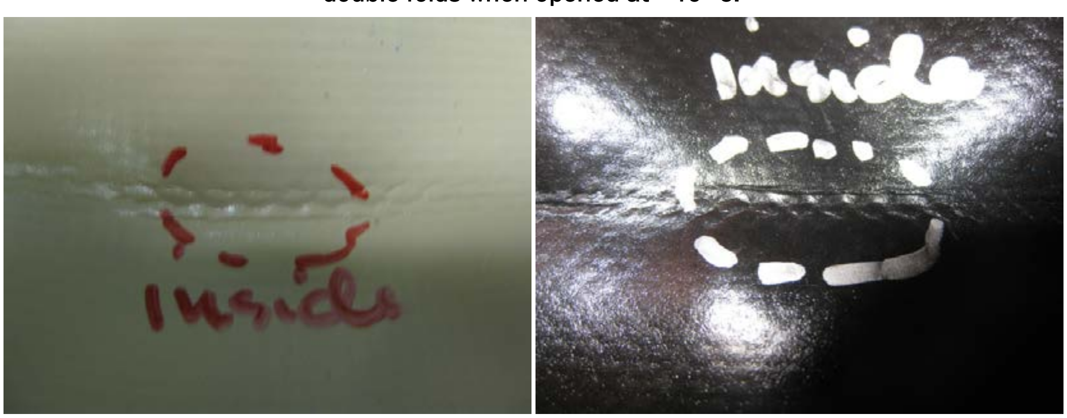


Figure 14. Folded specimens tended to fold-up partially after opening, suggesting some stress relaxation did occur from clamping for 1–2 days.

6 Discussion

We modified ASTM Standard F392, *Standard Practice for Conditioning Flexible Barrier Materials for Flex Durability* (ASTM International 2011), or "Gelbo" test, to assess low-temperature flex durability of polymer-coated fabrics that are in-service or considered for use in lightweight polar fuel and cargo sleds. The main modification was to clamp flat, rectangular specimens between the mandrels rather than wrap cylindrical specimens around them. This modification allowed us reliably to test polymer-coated fabrics that stiffen considerably at temperatures below 0°C.

We are generally pleased with our modified Gelbo test. It imposed severe flexing and folding on fabric specimens at −40°C. Post-test visual inspection and air-permeability tests reliably revealed failures (cracks and leaks and coating delamination), and repeated Gelbo tests on identical samples produced very similar results.

Tests of existing bladder materials (ATL-853C tan and black) provided performance baselines, and these materials clearly out-performed alternatives in terms of the number of Gelbo cycles survived before the specimens cracked and leaked. Nevertheless, we were surprised to find that the number of cycles required to cause failures exceeded several hundred. Visually, test specimens appeared to undergo more severe contortions than in-service fuel bladders. So why do a significant proportion of bladders fail each year?

Outbound fuel transport causes very few bladder failures, indicating that existing bladders tolerate well the flexing, wrinkling, and fuel sloshing that routinely occur as sleds transit rough sastrugi. Our earlier full-scale laboratory tests of bladder sleds predicted this to be the case (Lever et al. 2010), and it is satisfying that field performance has borne it out.

Normal practice has been to fold and roll empty fuel bladders at South Pole for return transport. Tight folds with sharp corners result even when the crew takes care to minimize them. Crew observations suggest that cracks preferentially appear along fold locations when the bladders are unfolded and inspected at the start of the next season. This strongly suggests that tightly folding bladder material can crack the polymer coating and cause fuel leaks.

ATL and FFF have both noted that joints and seams in welded or bonded fabrics are designed to be stronger than the material itself. We have no cause to doubt this assertion as it seems to be good engineering practice. However, welded or bonded lap joints double or more the thickness of the material locally, and thicker materials will experience greater stresses if folded to the same radius. Because bladders have not preferentially cracked at seams, this does not seem to be a problem in service.

Simply folding empty bladders at South Pole at about −30°C does not likely cause bladder failures. The ATL-853C specimens survived 510–1010 Gelbo cycles at −40°C and 100 cycles at −50°C without cracking and leaking. Folding once at South Pole should not impose stresses more severe than the Gelbo tests.

The ATL-853C specimens also survived 10,000 vibration cycles at −40°C (±0.5 in. stroke at 0.5 s periods) without leaking, even when the specimens were folded lengthwise before being clamped in the apparatus. This suggests that vibration of folded bladders during return transport does not cause failures. We considered the possibility that bladders abrade against each other during return transport, but SPoT crew and our own observations indicate that areas near cracks do not show signs of abrasion.

Mere over-winter cold-soaking of bladders probably does not produce irreversible brittle transformation of the polymer-coated fabric. Our test with ATL-853C specimens cold-soaked to −70°C and tested at −40°C produced essentially identical results as those tested with a −40°C cold soak.

We did observe signs of a possible failure mechanism: long-term folded storage of bladders will relieve compressive stresses at the insides of sharp corners; subsequent unfolding will induce high tensile stresses that could crack the polymer coating. We attempted to simulate this process by allowing folded and clamped specimens to relax for 1–2 days before cold soaking and unfolding at −40°C. Interior sharp corners creased, but they did not leak. Still, the material experienced some irreversible damage with just one cycle. It is possible that compressive stresses relax completely in bladders folded and stored for several months, even at lower temperatures. Although they are usually brought indoors and allowed to warm up for a day before being unfolded, it is possible that the resulting tensile stresses are sufficient to crack the material in some fraction of the many such tight folds that occur in each bladder (Figure 2).

Because bladder failures appear to correlate with folds, we recommended that SPoT attempt to return and store empty bladders unfolded. SPoT12–13 tried this approach, filling emptied bladders with air at South Pole for return transport strapped to their respective HMW-PE sheets (i.e., replacing fuel with air in the bladder-sled assembly). They then stored entire sled assemblies over the winter at McMurdo with the bladders inflated and sleds secured against wind loads.

Recent feedback from the SPoT crew is very encouraging: inflated bladders retained air pressure over the winter, and assembled sleds were easy to extract from the surrounding snowdrifts. Retained air pressure suggests minimal leaks and is a superior quality check to pre-season visual inspection of bladders for cracks, and the bladder sleds were essentially ready to use right out of storage by simply filling bladders with diesel fuel—no assembly required. Compared with folded storage, this method could significantly increase bladder life plus reduce the labor cost to disassemble, fold, store, unfold, inspect, and reassemble bladders on sleds each year.

Our modified Gelbo test also provided a reliable way to compare the low-temperature flex durability of fabrics considered for use in lightweight ARCS. Again using in-service material as a baseline (Sample 6, used in pouches supplied by FFF for PIG11–12 and GrIT12), the test allowed us quickly to screen candidate alternatives. FFF Samples 17 and 18 were clearly more durable and more flexible than Sample 6, and we recommended the black version, Sample 18, for use in the next series of ARCS pouches.

7 Recommendations

We provide the following recommendations based on low-temperature flex-durability (Gelbo) tests:

- Antarctic traverses should continue to use fuel bladders constructed from ATL-853C (black) polyurethane-coated fabric as supplied by Aero Tec Laboratories.
- If possible, transport and store empty bladders unfolded or inflated to reduce the potential for material failure (cracking and leaking) resulting from unfolding the bladders. Compare rates of bladder failures with traditional folded storage.
- Continue to procure ARCS pontoons constructed using the two-layer air beam system developed by FFF.
- Procure ARCS pouches constructed using Sample 18 material from FFF or its equivalent as assessed through low-temperature Gelbo tests.

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10-06-2014

2. REPORT TYPE
Technical Report/Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Low-Temperature Flex Durability of Fabrics for Polar Sleds

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
James H. Lever, Jason C. Weale, and Glenn Durell

5d. PROJECT NUMBER

5e. TASK NUMBER
EP-ANT-12-47 / EP-ANT-13-46

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Cold Regions Research and Engineering Laboratory (CRREL)
U.S. Army Engineer Research and Development Center (ERDC)
72 Lyme Road
Hanover, NH 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CRREL TR-14-24

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Science Foundation, Division of Polar Programs
Antarctic Infrastructure and Logistics
Arlington, VA 22230

10. SPONSOR/MONITOR'S ACRONYM(S)
NSF

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Engineering for Polar Operations, Logistics, and Research (EPOLAR)

14. ABSTRACT
Lightweight fuel-bladder sleds are remarkably efficient and less expensive than conventional steel sleds for Antarctic resupply traverses. However, a significant fraction of fuel bladders develop cracks after being emptied and folded for return transport and storage. We conducted low-temperature flex-durability tests of existing and candidate bladder materials to understand the fold-cracking problems and to seek more durable materials. The fabric specimens underwent repeated cycles of severe twisting and folding at −40°C, after which the specimens were checked for leaks by using an air-permeability test. Remarkably, the existing bladder material could withstand hundreds of cycles before cracking and leaking, and it performed better than tested alternatives. We speculate that months-long folded storage of bladders causes stress-relaxation in the polymer coating at tight folds, and pre-season unfolding then induces tensile cracking. In 2013, the South Pole Traverse (SPoT) acted on our recommendation to transport and store empty bladders inflated. They reported very promising results: no leaks in bladders and shorter preparation times for sled reuse. The flex-durability tests also identified very durable materials to build enclosure pouches for air-ride cargo sleds (ARCS). ARCS have the potential to transport rigid and out-size cargo as efficiently as fuel in bladder sleds.

15. SUBJECT TERMS
Antarctica
EPOLAR
Fatigue cracks
Flexibility
Gelbo test
Greenland
Lightweight sleds
Polymer-coated fabrics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	39	